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SOME OBSERVATIONS AND EXPERIMENTS ON JOINT PLANES

PEARL SHELDON

II

EXPERIMENTAL WORK

Systems of cracks at right angles to each other were obtained by Daubrée[1] by twisting plates of ice and glass and by compressing mixtures of beeswax and resin. W. O. Crosby[2] found that if plates twisted not quite to the breaking-point were given a shock they would break in cracks at right angles to each other. Systems of cracks due to torsion have been studied experimentally by G. F. Becker.[3] For this reason and because the conditions involved in the torsion experiments do not agree closely with the conditions under which the joint planes of this region were formed, these experiments were not repeated.

Theoretically and practically work similar to Daubrée's pressure experiments seemed most likely to give satisfactory results. Daubrée applied pressure over the square ends of blocks of wax. The sides were left unconfined so that deformation could take place on all sides. Besides large planes of slipping, the deformed blocks showed a network of fine even cracks at right angles to each other and parallel to the larger breaks. Daubrée compared the larger breaks with faults and the smaller with joints. Unfortunately, the outcrops of the cracks, though at right angles to each other, made angles of 45° with the direction of pressure, and, judging from his figures, the planes of breaking were parallel to the faces of an octahedron. This does not agree well with the commonly observed angles between joint faces, and the usual strike and dip relation of joints indicates that they are nearly at right angles to, and parallel to, the pressures acting at the time they were formed.

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[1] *Etudes synthétiques de géologie expérimentale*, 300–52.

[2] *Am. Geol.*, XII (1893), 368–75.

[3] *Trans. Am. Inst. Mining Engineers*, XXIV (1894), 130–38.

Instead of beeswax and resin, mixtures of paraffin and resin were used in the experiments. Several precautions were necessary in order to obtain good results. Paraffin alone faulted with a slickensided surface along a plane making an angle of 45° with the pressure, but no fine cracks appeared. The addition of a little resin, however, brought the desired cracks. The amount of resin used varied from just enough to stain the paraffin yellow to enough to give it a brown color. No good results were obtained with the material above a freezing temperature and the best results were had at about 0° F., or, rather, at the lowest temperatures available. Artificial cooling did not give such good effects as those obtained by allowing the material to harden by exposure to the air on the coldest winter days and subjecting it to pressure at the same temperature. The paraffin was cooled in tins and cut into convenient sizes while soft. It was found that the cracks came out better on the natural upper surface than on the smoother, glazed sides and bottom which had been in contact with the tin and better than on surfaces which had been planed smooth. This made it necessary to cool the paraffin carefully; otherwise, with its large contraction, the surface became badly wrinkled. It was also found best to cool the material rapidly and use it as soon as hard. The better results seemed to be connected with lack of uniformity in the material. Results were better on the less regular surfaces and on material so recently cooled that it probably was not equally hard throughout. Likewise, since it was cooled by being placed on snow with the upper surface exposed to the air, the rates of cooling of the upper and lower surfaces were different, with a consequent variation in grain through the mass. Daubrée was careful to have his blocks regular in shape, with faces planed smooth, and probably his material was nearly homogeneous. The experiments on paraffin showed that such care was more than wasted in preliminary experiments like these, where no attempt was made to use carefully regulated conditions for the purpose of obtaining mathematical results.

In size the blocks used were from two or three to eight or ten centimeters in length and breadth and from less than a centimeter to three centimeters in depth. These dimensions were employed in all combinations of long and narrow to square, thick, or thin.

The blocks were compressed in a small hand vise and one or two of the dimensions of the blocks were often greater than the corresponding dimensions of the jaws of the vise. Little attempt was made to smooth the paraffin to regular shape; therefore the application of the pressure was often very uneven. The varying conditions made it possible to trace cause and effect, and, since several scores of blocks were compressed and each showed different effects in its different parts, the results may be taken as general for the given material and given conditions.

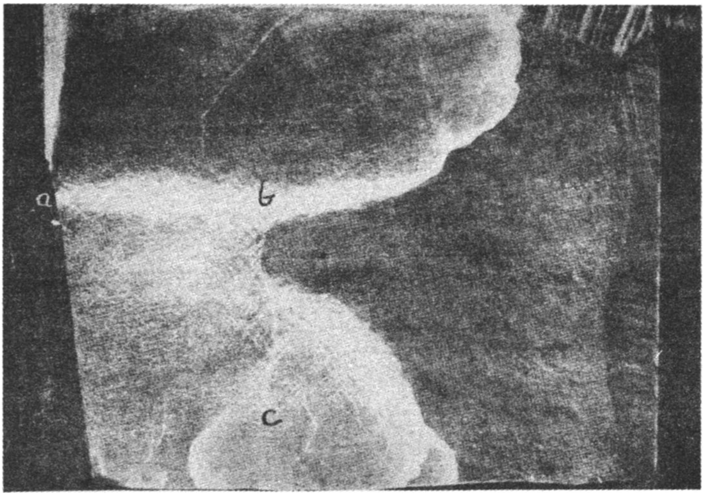

FIG. 9.—Photograph of a block of paraffin after compression. ×1.4

Figs. 9 and 10 are photographs of two of the blocks after they were compressed. The pressure was applied parallel to the plane of the paper in a line up and down the page. These blocks were hardly of average value for study but they were stained so dark with resin that it was possible to photograph the white cracks. Attempts to photograph the lighter-colored specimens by transmitted light were only partly successful. Fig. 11 is a composite showing the more common results of compression. The pressure was applied over the face *abcd* and the opposite face. Near the right edge is shown the result of a fairly even pressure over a rough face. With even pressure and a smooth face the material would break and slip with a slickensided surface along a plane making an angle of 45° with the pressure, that is, a plane whose outcrop on the face *abef* made an angle of 45° with the edges and whose outcrop on *bdfg* was a straight line parallel to the right edge. On account of the uneven face some points usually received a greater thrust than others so that the material broke in sections, the outcrops on the flat faces being parts of ellipses as shown in the figure. These sections each moved along a slipping plane of about 45° with the pressure, so that where there were several rows of semi-ellipses the material had been broken along several parallel slipping planes. The outcrop of the main slipping plane is shown from *h* to *i*. There was a similar tendency for the planes of slipping to break off the corners along the edges of the end faces. This is shown at *h* and *i* where the breaking plane extends farther in than it does near the center of the long edges. Sometimes this was carried so far that the point *h* was near the center of the shorter edges.

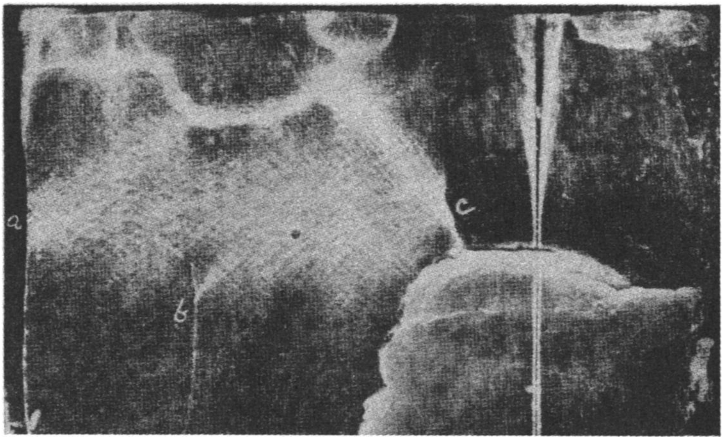

FIG. 10.—Photograph of a block of paraffin after compression. ×1.4

At the left edge is shown the result of a thrust which was stronger along the center of the face than near the edges *ac* and *bd*. In practice this occurred when the face of the material was wider than the jaws of the vise. The effect was usually to split the material in a nearly horizontal plane which, farther in, merged into a small slipping plane at 45° with the pressure with an outcrop along *jk*.

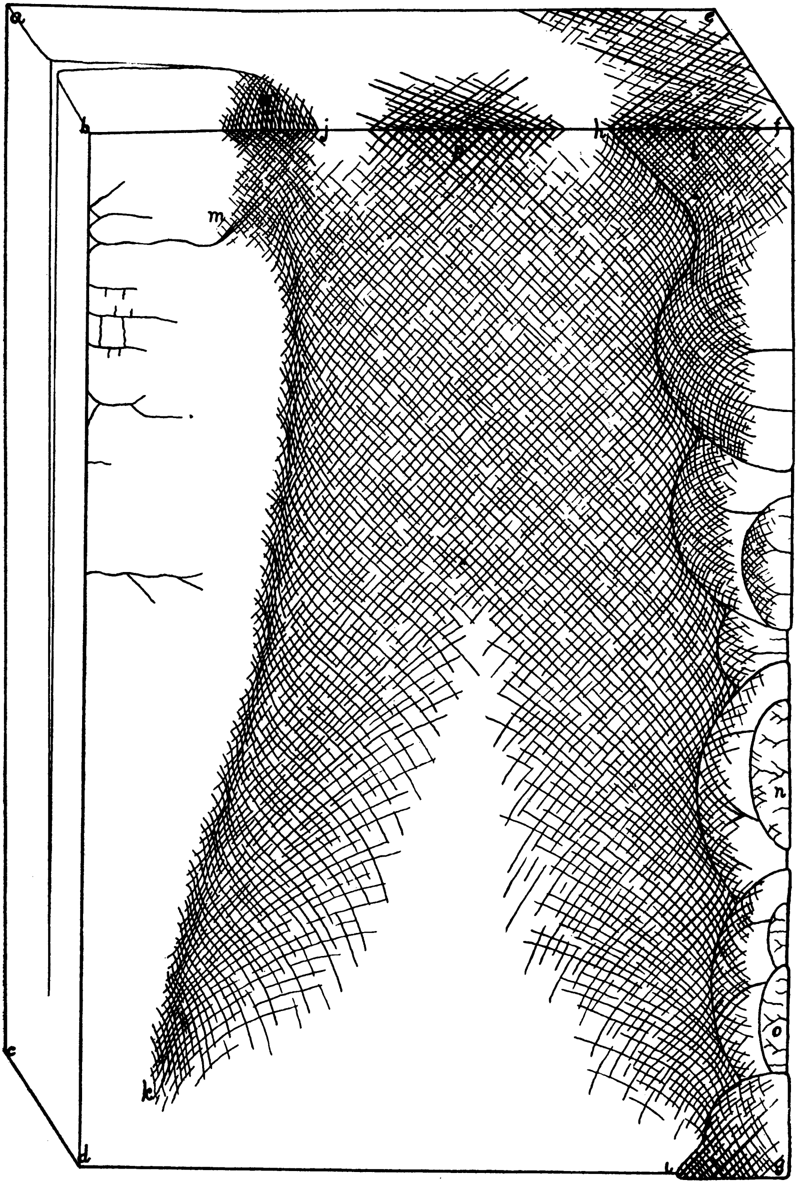

FIG. 11.—Composite showing the cracks produced by compression

Along *hi* slipping has taken place but *jk* represents the condition just before breaking at the surface. The outcrops of the slipping planes occurred on either the face *bfgd* or *aec* or both, depending upon the application of the pressure.

With the distance between the jaws of the vise small compared with the length and especially with hard material at the lowest temperatures, the blocks often broke in planes nearly parallel to the end faces *abef* and *cdg*. The break through the middle was nearly a plane face and the breaks toward the ends were convex outward, resembling a pile of thin cards compressed at the ends so that the cards bow out. In these breaks the faces separated instead of slipping on each other and slickensiding. With material cooled rapidly to a low temperature these faces were usually covered with even, featherlike markings which were of interest because they closely resembled the patterns which J. B. Woodworth[1] found on the faces of joint planes. The patterns consisted of a central smooth axis from which extended scales of the paraffin shaped like a half-crescent with the point toward the axis. The scales were free along the concave margin and passed into the material along the convex edge. The position of the axis of the feather depended on the application of the pressure and the homogeneity of the material but was usually near the middle of the breaking plane.

With similar hard material and the pressure applied to points as along *fg* the breaking took place along surfaces shaped much like half a bell with the rim in the face *bfdg*. These bell-shaped surfaces were also covered with half-crescent scales with their points toward the place where the thrust was applied and their broader portions radiating outward.

Such markings are associated with separation of faces rather than slickensiding. Further study of them might be of interest in connection with the question of whether joint faces are separated at some time in their formation or are always held tightly together. Such markings were not seen on the joint faces of the Ithaca region.

NETWORK OF CRACKS

Besides the large breaks, there was a system of intersecting even cracks similar to the fine network found by Daubrée. He compared them with joints. Their behavior under various conditions of pressure and breaking of the material is shown in Fig. 11 and the photographs.

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[1] *Proc. Boston Soc. Nat. Hist.*, XXVII (1896), 163–83.

Perhaps the most conspicuous result of the experiments on paraffin concerned the relation between these cracks and the forces at right angles to the active pressure. Whatever the direction of the cracks in the inner part of the block, whenever they approached the unconfined edges they turned so that their outcrops made angles of 45° with the edges. This is shown at *j*, *l*, and *i* in Fig. 11 and at *a* in Fig. 10. At *a* in Fig. 9 the same thing was present but the change occurred abruptly so near the edge that it did not show in the photograph. The cracks also turned or strengthened when they approached larger breaks as shown at *m* in Fig. 11, at *b* and *c* in Fig. 10, and from *b* to *c* in Fig. 9. Wherever these fine cracks approached free edges they immediately turned to the 45° position. In practically all cases the cracks became stronger near such edges as is shown in the photographs and indicated in the drawing.

Obviously, in rocks there would be few such places where the material acted on ended abruptly. In practically all cases deformation would be resisted by strong molecular forces at the sides and usually by the influence of overlying beds. Hence the cracks obtained by Daubrée and those at the edges and surfaces of the paraffin blocks could not be expected closely to imitate joints. More satisfactory results would be expected near the center of the block where the molecular forces would have a normal effect.

Near the edges there were often irregular cracks making small angles with the pressure like those shown at the left edge of Fig. 11. On the smaller semi-elliptic surfaces they were often forked, as at *n* and *o*, so that the portions of the break made equal angles with the line of pressure. Usually at some distance from the edge and beyond these irregular breaks the network of cracks appeared. They usually started at a fairly even distance from the edge, though often a few extended backward to the edge. At first they made oblique angles with each other, the line of pressure bisecting the acute angle. Soon they spread to right angles and then to larger angles near the outcrop of the slipping plane *hi*. There the line of pressure cut the obtuse angle. The cracks sometimes became nearly perpendicular to the line of pressure and appeared as a mass of wavy lines as at *ab* in Fig. 9.

Where the application of the pressure split off part of the block as along the left edge of Fig. 11 the cracks usually started farther from the edge and omitted the acute-angled portion as along *jk* in Fig. 11 and *ab* in Fig. 9. Thus near the outcrop of the slipping planes these cracks were nearly parallel to the outcrop and were arranged symmetrically about the line of pressure.

The preceding are the forms of cracks which were most common but in the better specimens the central part of the block was usually covered with cracks and these were more regular than in the rupture portions of the paraffin. They occurred evenly over the large faces, commonly making angles of 90° with each other and 45° with the pressure. At their connection with the oblique-angled cracks near the slipping planes the angles changed rapidly. These cracks were usually stronger near the center of the end edges, as at *p* in Fig. 11, than at each side of the center. In the block shown in Fig. 10 the breaking lines corresponding with *jk* in Fig. 11 both occurred near the center so that the cracks across the center showed a compromise between the large angles near the breaking lines and the right angles of the unbroken center of a block.

In Fig. 11 is shown the effect of a greater thrust near one end of the block. This was commonly caused by a greater width of the block at one end. Where the thrust died out the cracks were not symmetrical about the general line of pressure. This is shown in the lower central part of Fig. 11. Sometimes locally, as near an irregular breaking edge, a few cracks would occur in nearly the shape of a fan, one set forming a few rays and the other set curving at right angles to the rays.

Since the diagonal cracks made angles of 45° with the edges of the end faces, the planes of the cracks near the ends were nearly parallel to the faces of an octahedron. The inclination of the cracks near the center of the block could not be determined, but in some cases where the oblique cracks continued to a point near the edge the outcrop on the end faces was less than 45° with the vertical, as shown at *q* in Fig. 11. Probably the inclination varied as much from 45° as the direction did in the parts of the block away from the influence of the ends.

Fig. 11 shows the general appearance of the cracks with the exception that the lines were seldom sharp except near the edges. They were usually blurred by the crushing of the material, as shown in the photographs.

Closer examination of some of the diagonal cracks on the upper faces showed that the lines were not continuous but consisted of a series of more or less sigmoid lines arranged in diagonal rows, as shown on an enlarged scale in Fig. 12. Sometimes the diagonals consisted of a series of steplike fine cracks, as shown in the lower left-hand corner. Evidently where the thrust was sufficient to cause rupture the breaking took place along the diagonals, but a lesser thrust left the series of smaller cracks which had been formed first. These cracks were usually a millimeter or two in length.

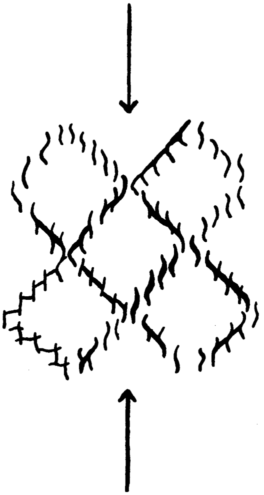

FIG. 12

FINEST CRACKS

When the material was examined by transmitted light with a hand lens it was found that still other cracks were present. Over the upper surface were many lines like those shown enlarged in Fig. 13. They looked like rift in granite.[1] They were about a millimeter long and were fine and sharp. They occurred especially where the thrust was unusually strong, in front of the semi-elliptical breaks, though they were often present between the slipping plane and the face where the pressure was applied. They often

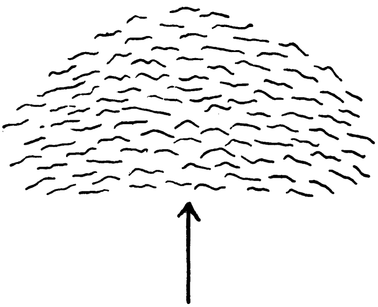

FIG. 13

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[1] R. S. Tarr, *Am. Jour. Sci.*, 3d ser., XLI (1891), 267–72.

occurred in the same places as the larger diagonal cracks, so that the surface showed two sets of opaque 45° cracks with these fine, wavy lines superposed upon them over the whole surface and arranged nearly at right angles to the pressure. Where the thrust decreased laterally there was a suggestion of a change in direction which would make the average direction of the cracks slightly concave toward the thrust.

When the paraffin was pared down so that a section from the interior could be studied by transmitted light it was found that in sections several millimeters thick there were opaque diagonal lines, but these lines no longer made angles of 90° with each other and 45° with the pressure as at the surface. The angles between the two were usually about 70°, with the line of pressure bisecting the acute angle. These were commonest where the thrust was unusually strong.

When the paraffin was cut to a thickness of about a millimeter these opaque lines disappeared and the material was seen to be full of fine, sharp, wavy cracks about a millimeter long like those shown in Fig. 13 but parallel to the pressure. Examination with a hand lens did not show that they were arranged in diagonal rows, but, since it was found uniformly that a thicker section gave broad opaque lines and these lines disappeared entirely in a thin section and fine wavy lines appeared in their place, it seemed, from analogy with the sigmoid lines and diagonals of the upper surface, that the breaking within the mass of paraffin consisted of fine cracks nearly parallel to the pressure, the cracks arranged in diagonal series so that by superposition they gave opaque lines in a thick section.

Thus in passing from the unnatural surface conditions to the interior of the mass where conditions would be more similar to those in the rocks the angles between the larger lines decreased so that the lines made a smaller angle with the pressure and the smaller cracks of which each line was made became straighter and entirely separated from each other. Here was a set of cracks uniformly present within the mass subjected to pressure, the cracks each nearly parallel to the line of pressure and suggesting an arrangement in two sets with the pressure bisecting the acute angle.

Unfortunately the fine lines at right angles to the pressure which were seen abundantly on the surface were not found within the mass, though certain fine lines may have been their representatives. If so, they were smaller than at the surface and too fine compared with the grain of the material itself to be studied with any accuracy. All of these finer cracks, both at right angles to, and parallel to, the pressure, could be studied only in thin sections by transmitted light and required a lens, but they were practically the same throughout the large number of specimens in which they were found, so that their general character was evident. The cracks were too fine for a determination of their inclination, but it probably was not large, since the cracks appeared as sharp lines instead of broad, opaque lines as would be the case if they ran diagonally through the material. Both of the sets of finer cracks appeared in the central unruptured portions of the paraffin as well as in the broken parts. The material appeared unbroken but when it was held before a light the places of greater thrust were found to be opaque, and examination with a lens showed the fine lines which caused the opaque appearance.

The experiments were carried about as far as possible under these conditions, since the most interesting cracks were too fine for study with the naked eye and the irregularities of the material were large compared with the size of the cracks. Further study should be made with finer-grained material which could be studied with a microscope, or the conditions should be such as to give larger cracks.

DEDUCTIONS

AGE OF THE JOINT PLANES

STRIKE JOINTS

It is apparent that the strike joints were formed in connection with the low folds of this region. Their average strike corresponds too closely with the axes of the folds to be accidental. If they had been formed before the folding with a uniform, nearly vertical inclination they would now be nearly at right angles to the bedding planes; that is, if the planes of the joints were produced they would meet below the axes of anticlines and above the axes of synclines. The reverse was found to be true. If they originally made a uniform moderate or large angle with the vertical, folding would have increased the angle on one limb of the fold and decreased the angle or reversed it on the other. Thus angles such as were actually found might be produced on one limb of the fold but not on the other. If the joints had a varying hade which reversed near the axes of subsequent folds the present angles might be produced, but that is too improbable.

The joints might have been formed with uniform, nearly vertical inclination after the beginning of the folding. Subsequent subsidence of the folds would give the angles observed. This is not probable, because the faulting indicates that much of the movement took place after the formation of the joints. This theory would require a reversal of all the later folding and enough more to reverse the joints. It would not alter the question of the age of the joints, since, if their hades were produced in this way, they must have been formed during the folding.

The upper limit for the date of the jointing is set by the faulting. The nearly horizontal faults of this region uniformly displace the joints which they cross; therefore the joints were formed before the faulting, or at least before the end of the movement along the fault planes. These faults were presumably formed in the time of active folding here, that is, during the Appalachian Revolution. This sets the date of the joints as somewhere between the beginning of the pressure which caused the folds and the climax of the folding as indicated by the active faulting. Unless the joints were formed by subsidence of the folds their direction of inclination is, in most cases, the same now as when they were formed. The angles, however, have been altered by later folding and in some cases may have been reversed. This may explain some cases where the reversal of direction takes place at one side of the axis of a fold.

DIP JOINTS

The evidence for the dip joints is not so conclusive, since the lack of detailed knowledge of the pitch of the folds prevents a comparison of the variation of the hade of the joints with the variation of the folds. From what is known of the pitch the hade of the dip joints seems to be mainly in the same direction as the pitch. At any rate, their hade is not such as would be produced by subsequent uplift of joints formed with uniform, nearly vertical inclination.

As in the case of the strike joints, the upper limit is set by the faulting. They cannot be older than upper Devonian, the age of the rocks in which they occur. One set of dip joints is nearly at right angles to the axes of the folds and the other set lies near the local resultant force acting during the folding as indicated by the strike of the faults. The angle between the two dip sets varies with the intensity and pitch of the folds. They are not so well differentiated near the weak Watkins anticline as near the strong and pitching Shurger Point fold and the strong Alpine anticline south of the Enfield syncline. The comparative strength of the two sets varies also. The experimental work showed that a variation in the forces at right angles to the active pressure had a large effect upon the cracks. The pitching of the folds and the large angle shown by the faults between the local resultant force and the general force at right angles to the axes of the folds indicate that the forces at right angles to the pressure varied considerably from place to place during the folding. Under such conditions the two dip sets would be expected to differ in strength and to vary with the folds if they were formed at that time.

The experiments showed that subjecting paraffin and resin to pressure gave fine cracks at right angles to the pressure and nearly parallel to the pressure. The latter were developed from a double set bisected by the line of pressure and might themselves form a double set if they could be measured carefully. During the Appalachian Revolution such a horizontal pressure was applied to the strata and should have formed cracks having directions like the observed joint planes. It has not been shown that there was enough disturbance of this region between the time of deposit of the rocks and the formation of the folds to have produced joints. If that were the case two independent groups of strike and dip joints should be found, for experimentally both strike and dip cracks were formed by a single application of pressure. There are two sets of dip joints found but they seem to be too closely connected to have been formed by entirely separate forces and the strike joints distinctly belong to a single set.

It has sometimes been assumed that joints at right angles to each other were formed at separate times, the forces producing the second set being at right angles to the forces producing the first set, that is, both sets bore the same relation to the forces which caused them but the forces were in different directions the two times. Opposed to this is the fact that the strike and dip joints are not similar. If a certain set of forces produced the strike joints, then a similar set of forces acting at right angles to the former forces should give another set much like the strike joints except in direction. This is not the case in the Ithaca region. Experimentally cracks were produced in all the required directions during the same application of pressure and it does not seem necessary to assume that strike and dip joints were formed by separate applications of pressure in the rocks.

In most cases the master joints are sharply cut by the faults but in some cases there is evidence that some strain existed along the fault planes at the time the joints were produced. Near the right in Fig. 1 is a dip joint which is strong and normal excepting near the fault line where it abruptly breaks into a fanlike set of radial small cracks with the point below. This fan is about a foot across and the fault crosses its center. Above the fan the joint becomes normal again. Evidently when the joint was formed there was some strain at the place where movement occurred later or perhaps the faulting had already begun. Many of these fanlike irregular joints were seen near faults and were evidently due to strain at the fault planes, but the others were not examined for their relation to the master joints. Investigation would probably show that more of these are connected with the master joints and in the case described the fan is certainly a part of an otherwise normal joint belonging to one of the dip sets.

The evidence thus indicates that all the master joints were formed in the earlier part of the period of folding. Probably when the pressure reached a certain value, less than its maximum, the joints were formed rather abruptly. Further pressure caused faulting, or perhaps some faulting occurred before the formation of joints and the continued pressure caused further slipping which displaced the joints. It is not necessary to assume that the strike and dip joints were formed at exactly the same time. They are unlike in other respects and may have been in this. In the experiments the fine cracks could not be watched as they were formed so that their time relation was not determined.

EVIDENCE OF THE DIKES

All the known dikes of this region are in the dip joints. None are found in the strike set. Kindle[1] has suggested that the dip joints were older than the Appalachian uplift and the igneous matter was intruded before the formation of the strike set. Another suggestion that has been made assumes that the faces of the strike joints were held tightly together by pressure so that the dike material could not force its way in. Opposed to this is the fact that many of the dike streamers are exceedingly thin, penetrating fine breaks.

The dikes are mostly in the Portage rocks and in these the dip joints are usually the stronger. Judging from the experiments the faces of strike joints would be held together but under some conditions there might be a tendency for the faces of the dip joints to separate. This would allow the igneous matter to enter the dip joints more easily. Perhaps the dip joints antedate the strike set, even though both were formed during the folding. Since the dikes are faulted, they were obviously formed between the time of the dip joints and the climax of the faulting. Further study of the relations between dikes, joints, and faults would probably be useful in determining the exact order of formation of the various sets of joints, but from the present evidence it does not seem necessary to assume that the dip sets were present before the Appalachian Revolution in order to explain the dikes.

The time of formation of the minor joints is not so evident. Probably most of them were formed at about the same time as the master joints. Along the walls of the dikes the rocks are cut by innumerable small jointlike cracks which were evidently formed as a result of the pressure of the dike material.

[1] *Folio 169*, p. 13; field edition, pp. 96–97.

The Ithaca region seems particularly favorable for the study of joint planes. The stratigraphy is comparatively simple, showing only one time of crustal movements sufficiently great to be accompanied by jointing. The pressure was strong enough to produce joints and folds and faults with which the joints could be compared, but it did not carry the folding far enough entirely to reverse the joints and so complicate the record. In regions of higher folds the hades of the joints should be studied with the plane of bedding rather than the horizontal as a datum plane.

CAUSE OF THE JOINT PLANES

Geologists are not agreed upon the cause of joint planes in stratified rocks. On account of the observed relation between joints and the strike and dip of rocks it is usually conceded that they are connected with movements of the earth's crust. Some of the theories of the cause of joints have been abandoned. Among those still recognized are tension, earthquake shock, torsion, and shear.

TENSION THEORY

According to the tension hypothesis joints are formed during folding. As the folds develop there is tension along the upper surface of anticlines and the under side of synclines. The rocks then crack in planes whose outcrops are parallel to the axes of the folds. At right angles to the axes the pitch of the folds causes another set, the dip joints. A general objection to this theory is the character of the joint faces. They are smooth and are remarkable for passing directly through hard masses like pebbles or concretions, instead of around them. The Hamilton shales of this region show this very well. The rock is mostly an even shale but there are several bands of hard concretions. Some of the joints do not pass through the concretions but probably the majority cut them in a smooth plane even with the rest of the joint face. It does not seem probable that a crack due to tension and separation of faces would pass so smoothly through concretions instead of around them. The general smoothness of a joint face in shale is very unlike the surface caused by breaking rock apart.

Joints formed by tension would be arranged radially about the folds, that is, if their planes were produced they would meet below the axes of anticlines and above the axes of synclines. The reverse was found to be true. It seems difficult to explain the hade of the strike joints by the tension theory. Neither does this theory account for the double nature of the dip joints nor for the mass of minor joints in all directions. The perfection of jointing in some parts of this region is out of proportion to the amount of cracking necessary to relieve the tension in such low folds.

EARTHQUAKE THEORY

W. O. Crosby[1] offered an earthquake hypothesis as an explanation of joints. Later[2] he emphasized the effect of shock on rocks already under strain rather than shock alone. Crosby stated some of the more important objections to the formation of joints by earthquake shock alone. Such breaks would not become approximately vertical for some distance from the epicentrum and then the energy of the shock would be largely dissipated. In the Ithaca region the inclination of the master joints is nearly vertical and in changing from one side to the other passes through the vertical, not through the horizontal as would be expected from earthquake waves. In order to explain the commonly observed right-angled relation of joints, it has been assumed that after one shock had produced a set in one direction a large component of a subsequent shock would be relieved by slipping along the already existing planes, unless it was at right angles to the earlier shock, except in case of very rapid vibrations. Only one set of planes would be formed by each shock. The direction of the strike joints might be accounted for by making the focus of the earthquake a long fault parallel to the axis of the fold. An objection to the earthquake hypothesis apparent in this region is the symmetry between the joints and folds. It is not probable that the folds would influence cracks due to earthquakes to such an extent nor is it probable that separate shocks occurred simultaneously in the different folds to cause a reversal of the joints near each axis.

The earthquake theory alone seems awkward, since it requires an improbable system of separate shocks to account for the several sets of major joints and the mass of minor joints. These shocks must have been symmetrical with the forces producing folding, and the resulting breaks were of different character at different times. It seems simpler to refer the joints mainly to the orogenic forces, but perhaps as in Crosby's combination of shock and torsion the shock attending crustal movements materially affects the formation of cracks in strained rocks.

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[1] *Proc. Boston Soc. Nat. Hist.*, XXII (1882), 72–85; XXIII, 243–48.

[2] *Am. Geol.*, XII (1893), 368–75.

TORSION THEORY

In Daubrée's torsion experiments the material broke in two sets of cracks, making angles of 90° with each other and 45° with the axis of torsion on the large faces of the plates. The inclination as shown on the narrow side faces was as high as 50° with the vertical, though usually less. Becker repeated these experiments with plates of glass of various dimensions. He obtained the same directions of outcrop on the large faces as were found by Daubrée and he also found that the breaking surfaces were curved. Sometimes the outcrop on one of the large parallel faces of the glass was straight and on the other S-shaped.

Many of the minor joints of the Ithaca region are shaped like the surfaces Becker obtained by torsion and they are probably due to this cause. The most important of the curving joints are those which strike north of west. The well-developed joints of large hade found near the Shurger Point fold also resemble breaks due to torsion. The innumerable small joint faces are probably due to local twisting.

The master joints do not show such curvature in a single exposure, though perhaps if their full extent were seen they would be found to have a twisted surface. The torsion theory has been criticized because the breaks make angles of 45° with the axis of torsion while joint planes are nearly parallel to the dip and strike of rocks. If the ends of a piece of cardboard are twisted in opposite directions the resulting ridge runs diagonally between the corners or nearly parallel to one of the sets of cracks obtained by Daubrée. In order to twist the plates, however, Daubrée applied a couple at right angles to the plane of the large faces. In the rocks this would correspond with a set of vertical forces. The pressure forming the folds of this region was tangential to the beds rather than vertical; therefore the conditions in the rocks were unlike the conditions of the torsion experiments, though there was probably some variation in the vertical forces. Moreover, in comparing the various theories for the formation of joints it may be considered that torsion like that employed by Daubrée is only a special case of shear.

SHEAR THEORY

Daubrée also obtained a network of cracks by a compression which caused shearing stresses. Becker[1] has given a mathematical treatment of strains in rocks and explains joints as the result of shear. The field observations show an intimate relation between the master joints and the forces which caused the folding. Those forces are supposed to have been tangential to the beds. The symmetry of the faults in the encrinal limestone about a nearly horizontal plane is evidence that, if not vertical, the chief forces were nearly horizontal. By applying pressure to the narrow faces of blocks of paraffin fine cracks were obtained which bore nearly the same relation to the pressure which the joint planes bear to the pressure active during the folding. The pressure used in the experiments corresponded with a tangential pressure on the strata. The evidence points toward the formation of the joints as the result of a nearly horizontal pressure, but in the present state of knowledge of the relations between stress and strain in rocks the relations between joints and the strains caused by this pressure are uncertain. Strains in rocks are exceedingly complicated, since the forces vary and the materials acted upon are not homogeneous.

The joints found here do not exactly agree with the breaks discussed by Becker. They are similar in some respects but unlike in others. He concluded that faults, joints, and slaty cleavage all lie in the planes of maximum tangential strain. This implies that joints are only faults of little throw. The faults in this region were apparently formed under the same set of forces as the joint planes; yet the two are very unlike. Of three planes at right angles to each other, the faults lie approximately in one, the horizontal, and the strike and dip joints lie approximately in the other two, the vertical planes. Slipping may occur in two planes which have the same strike. In the encrinal limestone both these slipping planes are represented by true faults.

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[1] *Bull. Geol. Soc. Am.*, IV (1893), 13–90; *Proc. Wash. Acad. Sci.*, VII (1905), 267–75; *Eng. and Mining Jour.*, LXXIX (1905), 1182–84.

If there was differential movement of the joint faces during the folding, that throw was not more than a fraction of an inch. On the other hand, there was displacement of half a foot along the fault planes after the formation of the joints. If joints lie in the planes where slipping would be expected to occur, it seems strange that under forces strong enough to cause noticeable displacement along known faults there was little or no movement along the joints if the latter are incipient faults. In the actual case found in this region the joints are so nearly at right angles to the horizontal faults that the force along the fault planes had almost no component along the joint planes, hence movement along the faults could take place without slipping along the joints even though they formed planes of weakness. If pressure is applied to the rocks at an oblique angle with the joint planes after the joints are once formed, slipping would be likely to result; but such subsequent movements are not an essential part of the production of the joints.

One of the difficulties in explaining joints by pressure theories has been the presence of a set of joints apparently parallel to the pressure. The Ithaca region shows that here, at least, the dip joints really consist of two sets not parallel to the pressure but more or less symmetrically arranged about the pressure and making a small angle with it.

If the faults lie in the true slipping planes then the small hades of the joints are still unexplained. Perhaps they are due to shock associated with the strains due to the pressure. The conditions under which the joints were formed probably included translation, rotation, compression, pure shear, some torsion of the kind employed by Daubrée, and shock. To determine the exact manner of formation of joints and their relations to stresses, there is need of detailed field observations on the relations between joints and the forces producing them, as indicated by attendant faults and the axes and pitch of folds, and need of experimental work by which cracks resembling joints can be produced under such conditions that measurements may be made to determine the relations between stress and strain.